MENU2010: 12th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon
May 31-June 4, 2010, College of William and Mary, Williamsburg, Virginia

E906/SeaQuest at FNAL:

Measurement of Flavor Asymmetry of Antiquarks in the Nucleons

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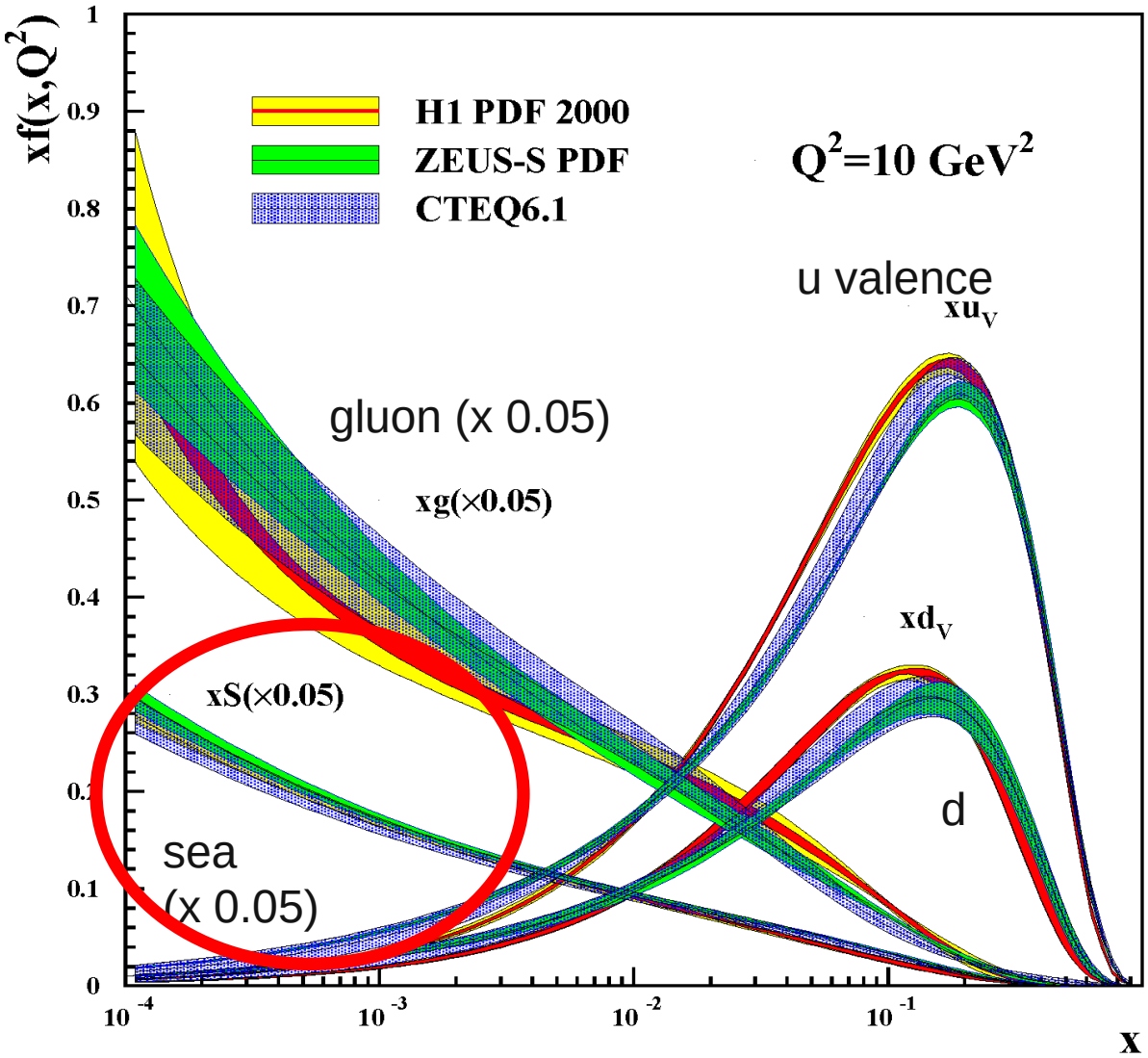
on behalf of E906/SeaQuest Collaboration

- **Introduction**
- **Explore sea quark content via Drell-Yan process.**
- **Observation of flavor asymmetry of sea quark.**
- **Interpretation of origin.**
- **E906/SeaQuest experiment at FNAL.**
- **Status and prospect.**

Unpolarized Parton Distributions (CTEQ6)

$$F_2(x,Q^2) = \sum_i e_i^2 x[q_i(x,Q^2) + \bar{q}_i(x,Q^2)]$$



Is $\bar{u} = \bar{d}$ in the proton?

$$F_2^p(x,Q^2) - F_2^n(x,Q^2) = \tfrac{1}{3}x[u_v(x,Q^2) - d_v(x,Q^2)] + \tfrac{2}{3}x[\bar{u}(x,Q^2) - \bar{d}(x,Q^2)]$$

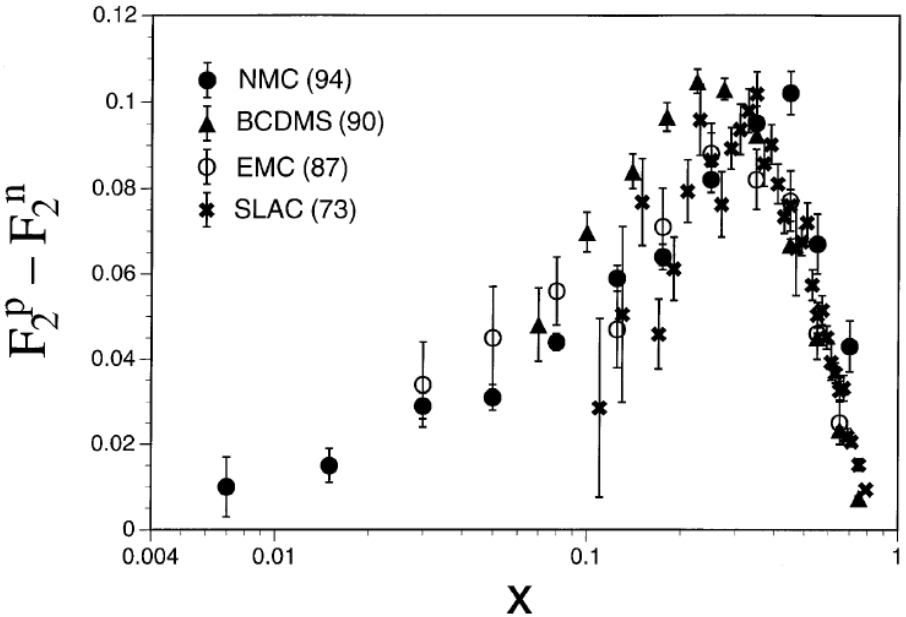
Gottfried Sum Rule

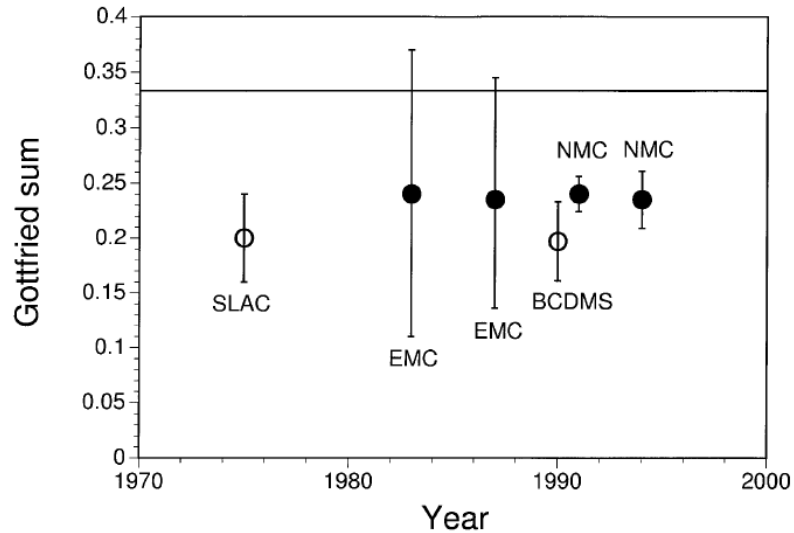
$$S_G = \int_0^1 [(F_2^p(x) - F_2^n(x))/x]\,dx$$

$$= \frac{1}{3} + \frac{2}{3}\int_0^1 (\bar{u}_p(x) - \bar{d}_p(x))\,dx$$

$$= \frac{1}{3} \quad (if\ \bar{u}_p = \bar{d}_p)$$

Experimental Measurement of Gottfried Sum





New Muon Collaboration (NMC), Phys. Rev. D50 (1994) R1

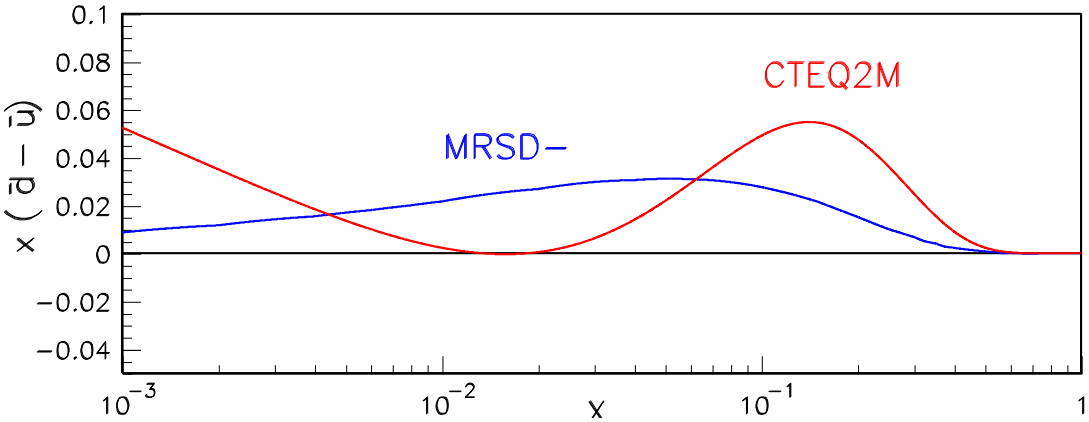
$S_G = 0.235 \pm 0.026$

(Significantly lower than 1/3 !)

Explanations for the NMC result

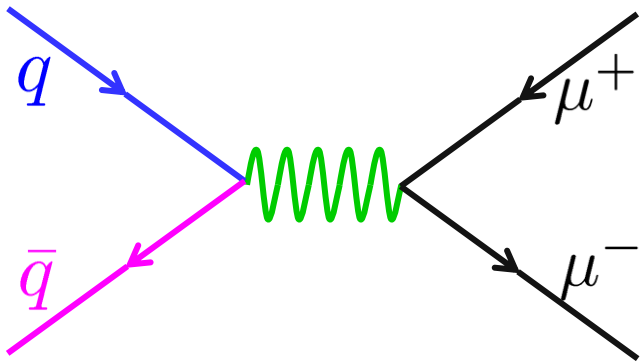
- Uncertain extrapolation for 0.0 < x < 0.004
- Charge symmetry violation $(\bar{u}_n \neq \bar{d}_p,\ \bar{d}_n \neq \bar{u}_p)$
- $\bar{u}(x) \neq \bar{d}(x)$ in the proton

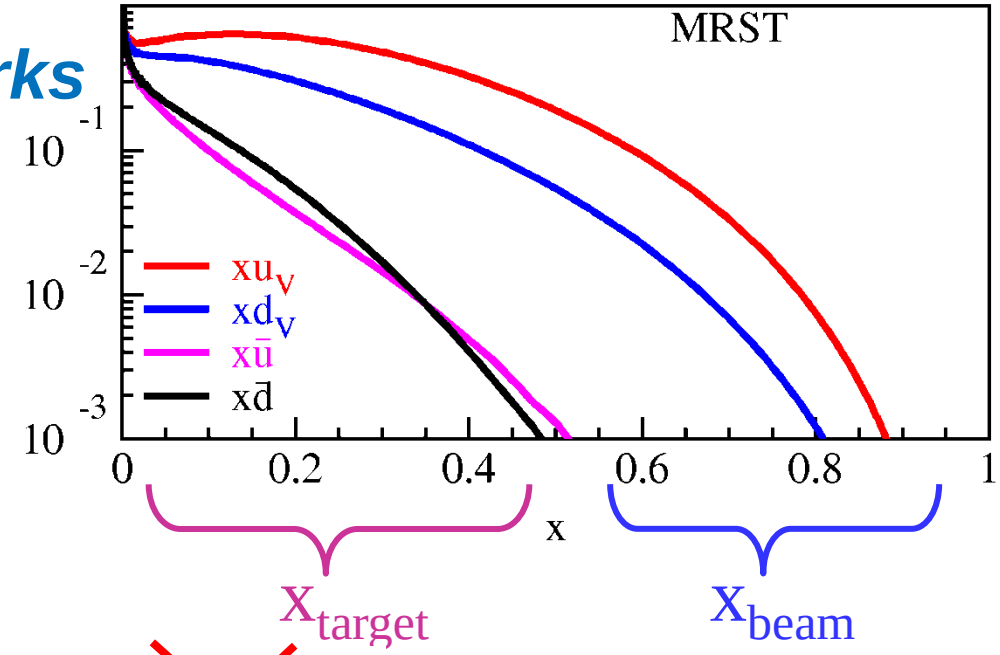
$$\int_0^1 (\bar{d}(x) - \bar{u}(x))\, dx = 0.148 \pm 0.04$$



Need independent methods to check the $\bar{d} - \bar{u}$ *asymmetry, and to measure its* ***x-dependence*** *!*

Drell-Yan process:
A laboratory for sea quarks



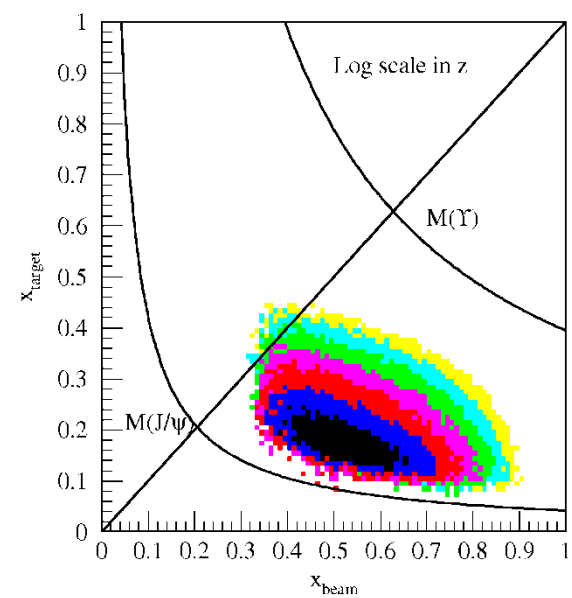


$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s}\sum e^2\left[\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)\right]$$

Detector acceptance chooses x_{target} and x_{beam}.

- Fixed target → high $x_F = x_{beam} - x_{target}$
- *Beam nucleon provides valence quarks at high-x.*
- *Target nucleon provides sea anti-quarks at low/intermediate-x.*
- Measure ratio of DY process from hydrogen and deuterium:

$$\frac{\sigma^{pd}}{2\sigma^{pp}}\Big|_{x1 >> x2} = \frac{1}{2}\left[\frac{1+\frac{d(x1)}{4u(x1)}}{1+\frac{d(x1)}{4u(x1)}\frac{\bar{d}(x2)}{\bar{u}(x2)}}\right]\left[1+\frac{\bar{d}(x2)}{\bar{u}(x2)}\right] = \frac{1}{2}\left[1+\frac{\bar{d}(x2)}{\bar{u}(x2)}\right]$$



Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:

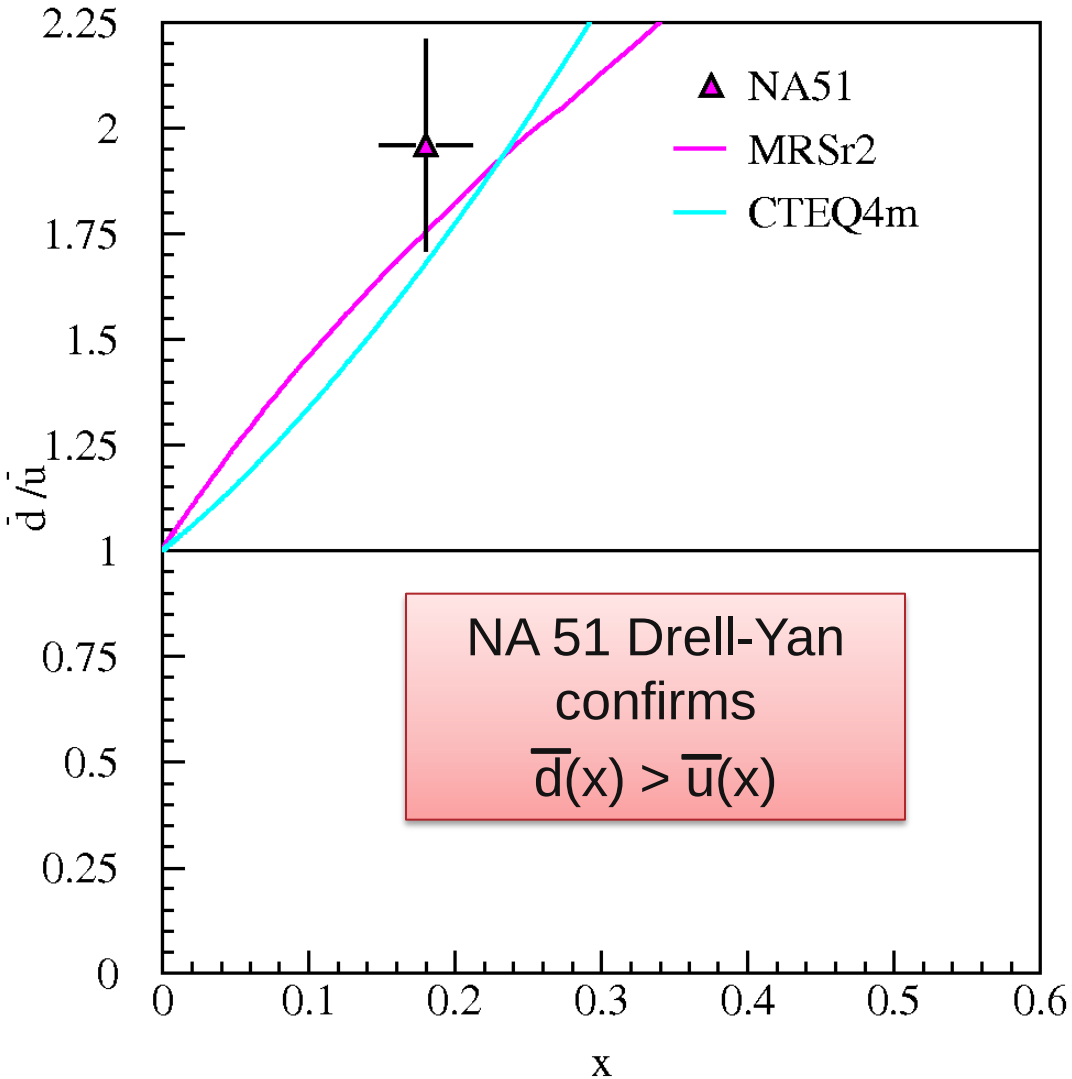
$$\bar{d}(x) = \bar{u}(x)$$

- NMC (Gottfried Sum Rule)

$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$

- NA51 (Drell-Yan, 1994)

$$\bar{d} > \bar{u} \text{ at } x = 0.18$$



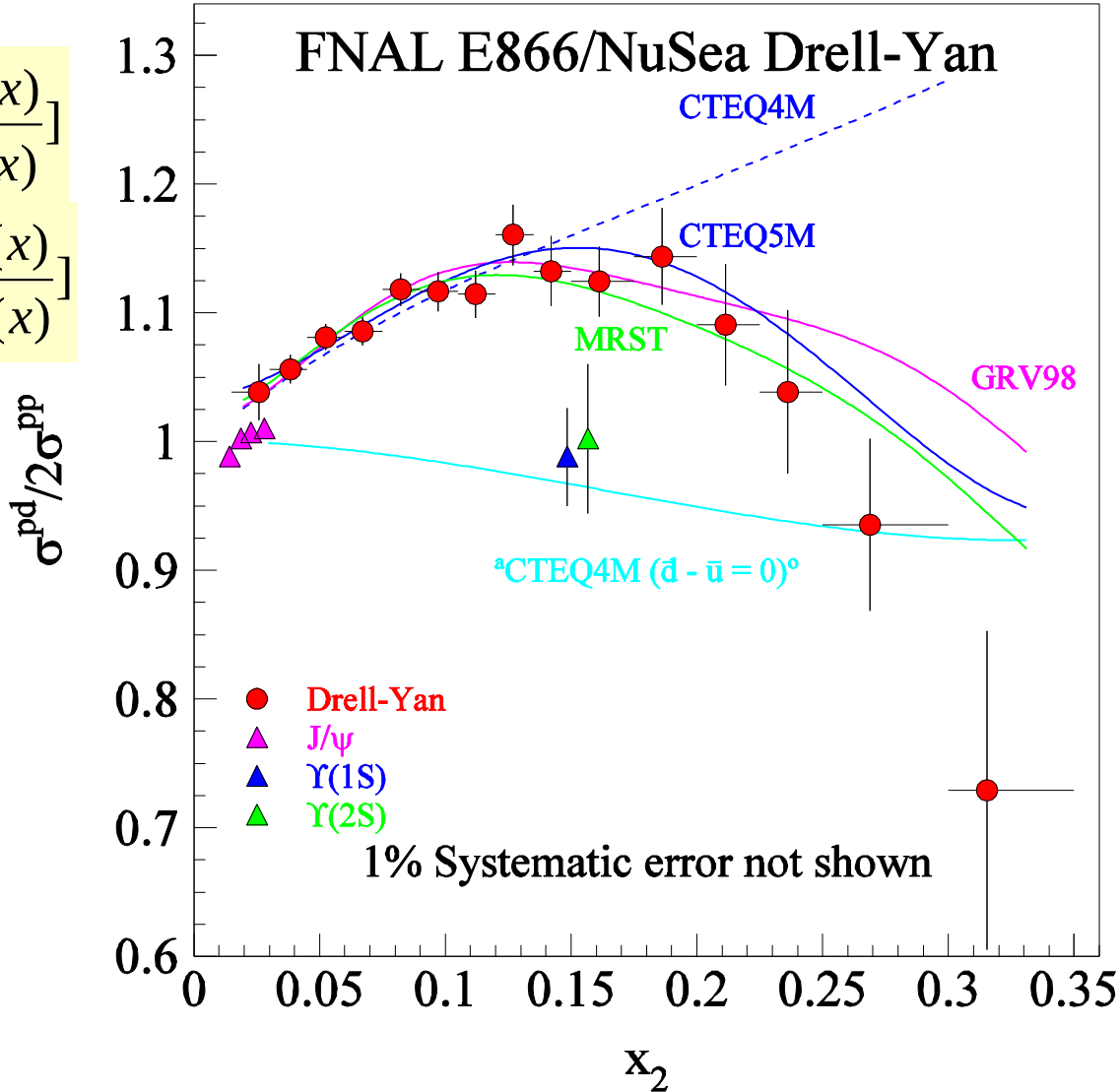
NA 51 Drell-Yan confirms $\bar{d}(x) > \bar{u}(x)$

Fermilab E866 Measurements

$$800\ GeV\ \sigma(p+d\rightarrow\mu^+\mu^- X)/\sigma(p+p\rightarrow\mu^+\mu^- X)$$

$$\text{Drell-Yan}: \frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}[1+\frac{\bar{d}(x)}{\bar{u}(x)}]$$

$$J/\psi,\gamma \quad : \frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}[1+\frac{g_n(x)}{g_p(x)}]$$



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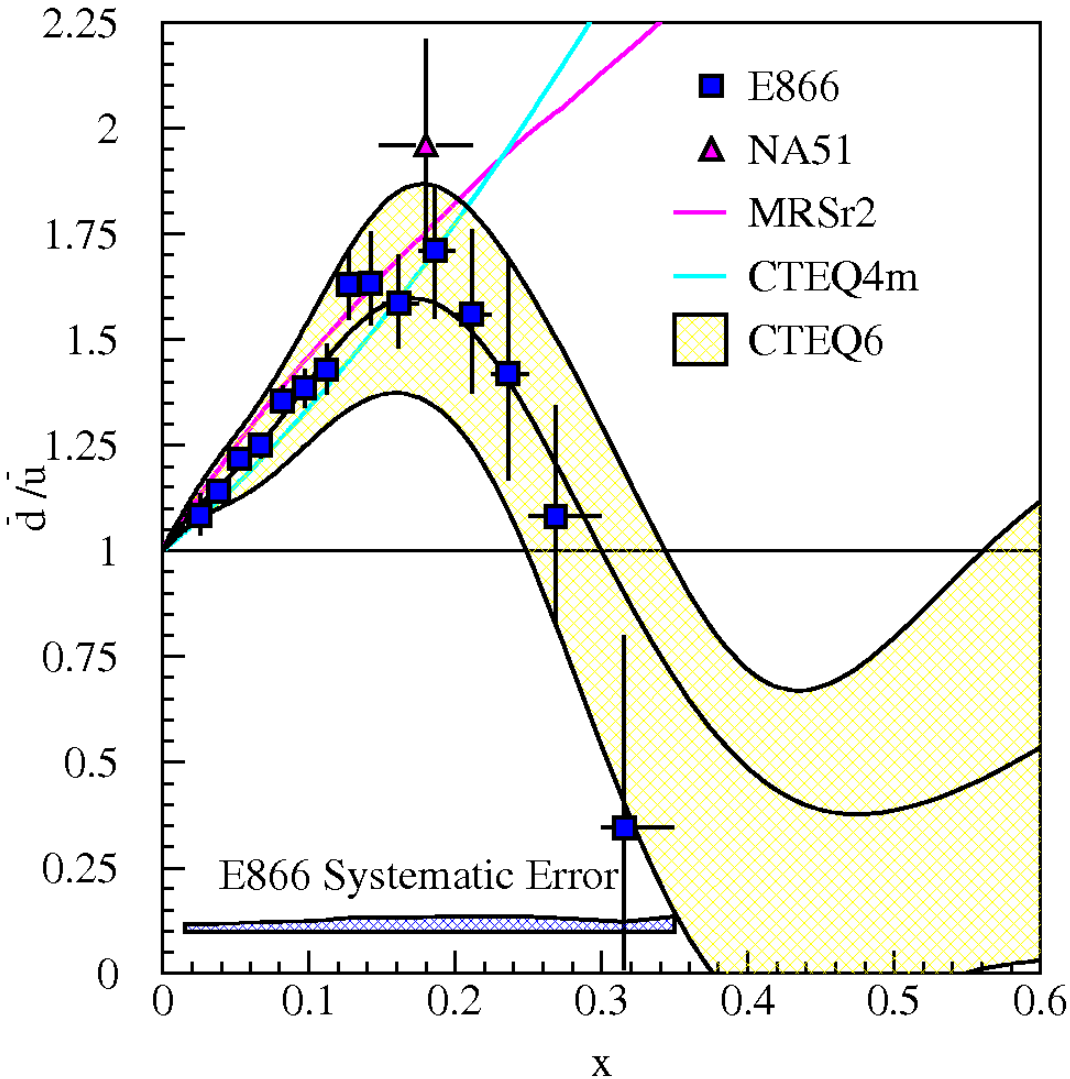
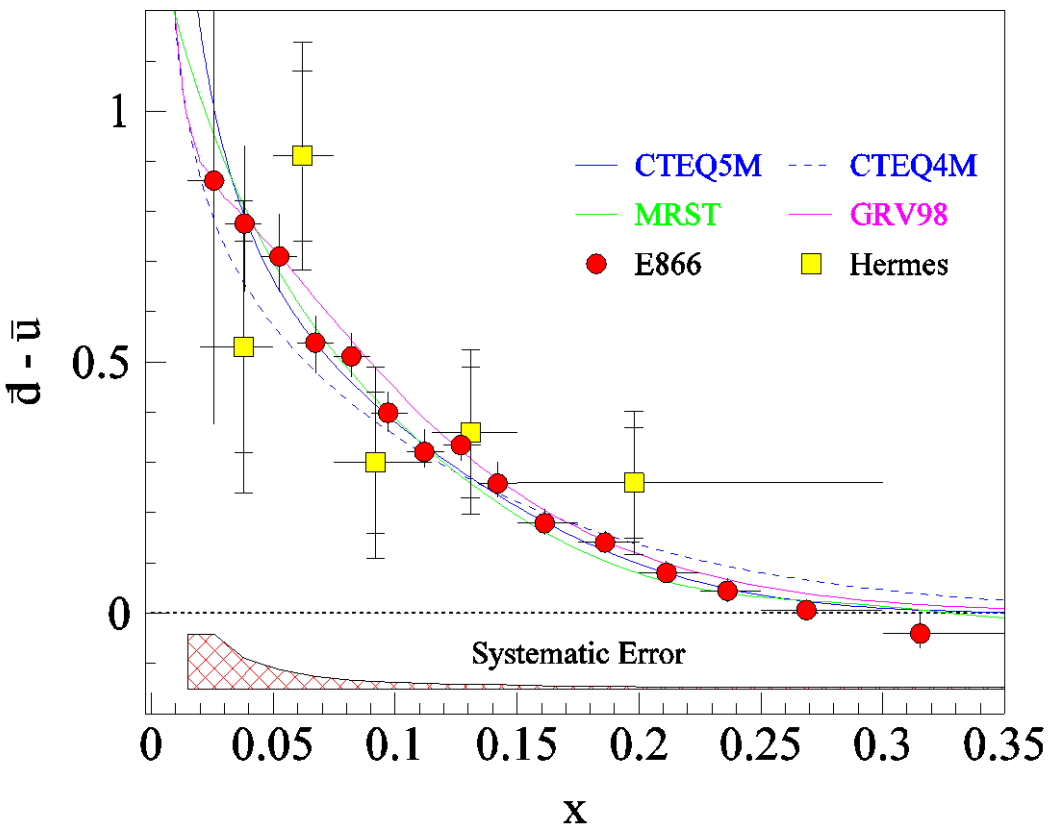
- E866/NuSea (Drell-Yan, 1998)

$$\bar{d}(x)/\bar{u}(x) \text{ for } 0.015 \leq x \leq 0.35$$



Extraction of $\bar{d}-\bar{u}$

$$\bar{d}-\bar{u}=\bar{u}\left(\frac{\bar{d}}{\bar{u}}-1\right)$$



$$\int_0^1[\bar{d}(x)-\bar{u}(x)]=0.118\pm0.011\ (E866)$$

$$\int_0^1[\bar{d}(x)-\bar{u}(x)]=0.16\pm0.03\ (HERMES)$$

$$\int_0^1[\bar{d}(x)-\bar{u}(x)]=0.147\pm0.039\ (NMC)$$

HERMES: Semi-Inclusive DIS

$E866:\ <Q^2>=54\,GeV^2;\quad HERMES:\ <Q^2>=2.3\,GeV^2$

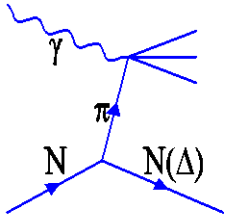
Origin of $\bar{u}(x) \neq \bar{d}(x)$: Valence quark effect?

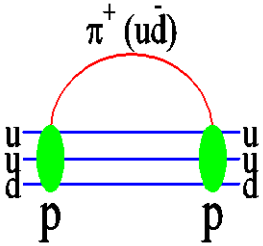
- **Pauli blocking**
  - $g \to u\bar{u}$ is more suppressed than $g \to d\bar{d}$ in the proton since p=uud (Field and Feynman 1977)
  - pQCD calculation (Ross Sachrajda)
  - Bag model calculation (Signal, Thomas, Schreiber)
- **Chiral quark-soliton model** (Diakonov, Pobylitsa, Polyakov)
- **Instanton model** (Dorokhov, Kochelev)
- **Statistical model** (Bourrely, Buccella, Soffer; Bhalerao)
- **Balance model** (Zhang, Ma)

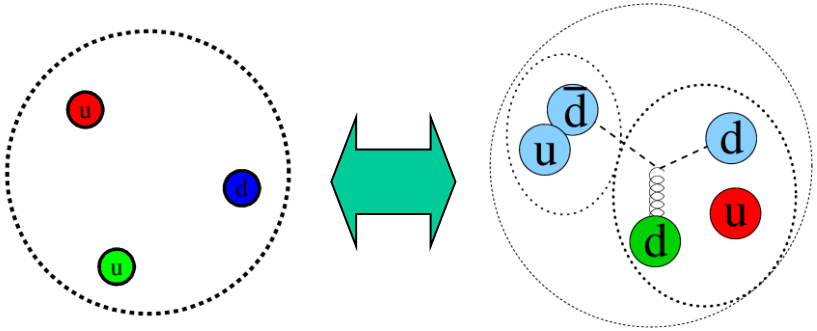
The valence quarks affect the Dirac vacuum and the quark-antiquark sea.

Origin of $\bar{u}(x) \neq \bar{d}(x)$: Non-perturbative effect?

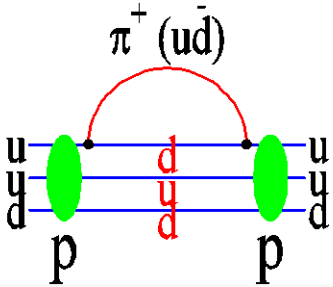
- **Meson cloud in the nucleons** (Thomas, Kumano): Sullivan process in DIS.







- **Chiral quark model** (Eichten, Hinchliffe, Quigg; Wakamatsu): Goldstone bosons couple to valence quarks.



The pion cloud is a source of anti-quarks in the protons and it lead to $\bar{d} > \bar{u}$.

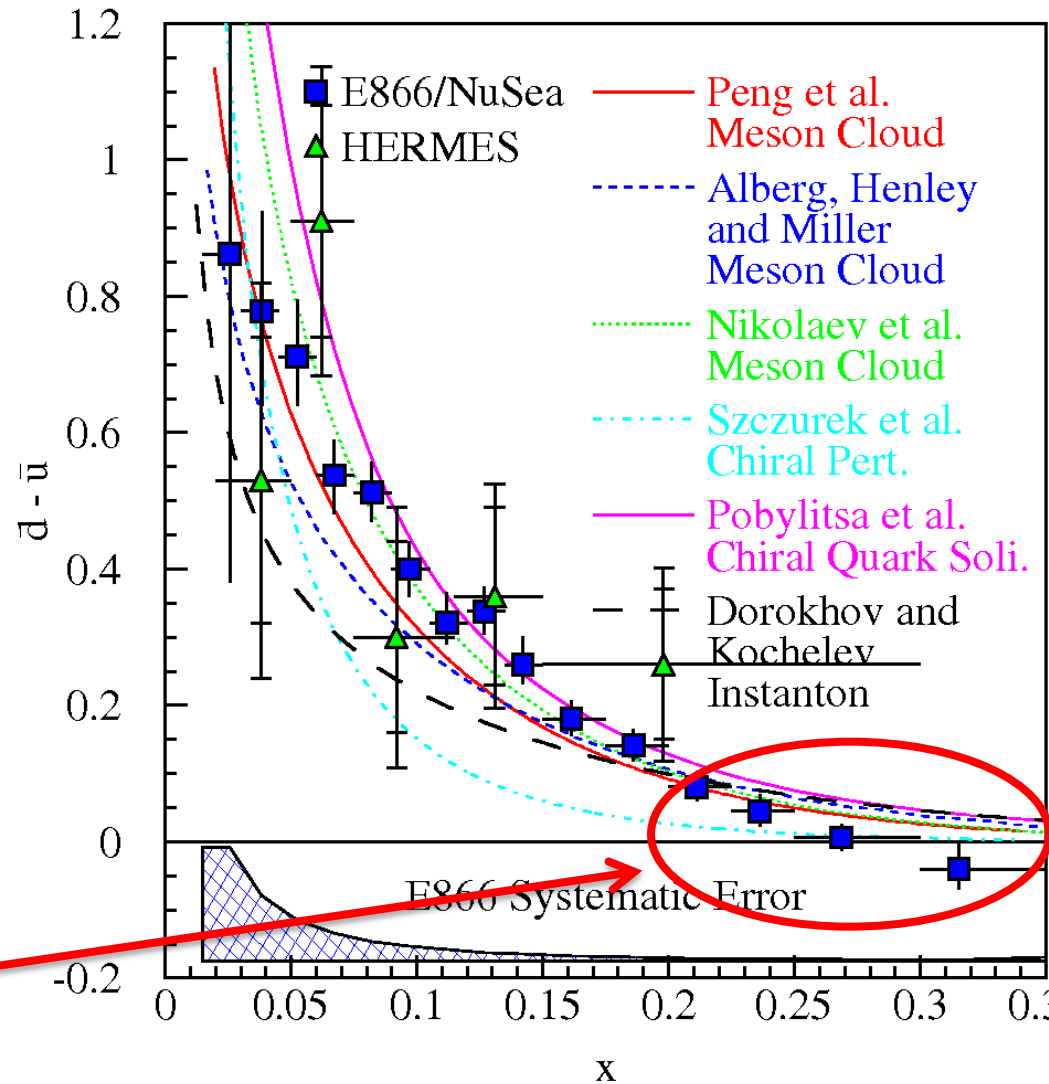
Proton Structure: Remove perturbative sea

- There is a gluon splitting component which is symmetric

$$\bar{d}(x) = \bar{u}(x) = \bar{q}(x)$$

- $\bar{d} - \bar{u}$
  - Symmetric sea via pair production from gluons subtracts off
  - No Gluon contribution at 1st order in α_s
  - Nonperturbative models are motivated by the observed difference

- A proton with 3 valence quarks plus glue cannot be right at any scale!!



Greater deviation at large-x

Advantages of 120 GeV Main Injector

The (very successful) past:

Fermilab E866/NuSea

- Data in 1996-1997
- ^{1}H, ^{2}H, and nuclear targets
- 800 GeV proton beam

The future:

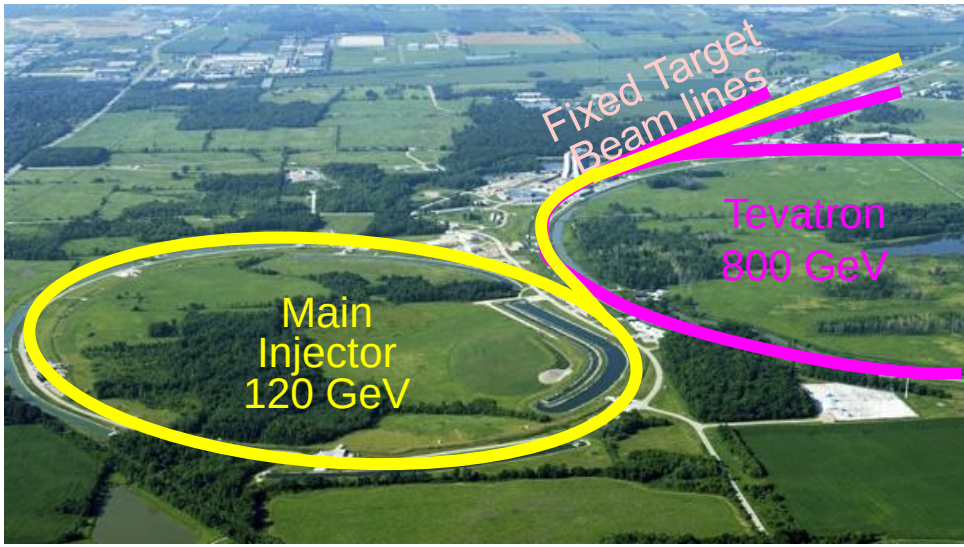
Fermilab E906

- Data taking planned in 2010
- ^{1}H, ^{2}H, and nuclear targets
- 120 GeV proton Beam

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1x_2}\frac{1}{s} \times \sum_i e_i^2 \left[q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)\right]$$

- Cross section scales as 1/s
  - *7x that of 800 GeV beam*
- Backgrounds, primarily from J/ψ decays scale as s
  - *7x Luminosity for same detector rate as 800 GeV beam*

50x statistics!!



E-906/SeaQuest Collaboration

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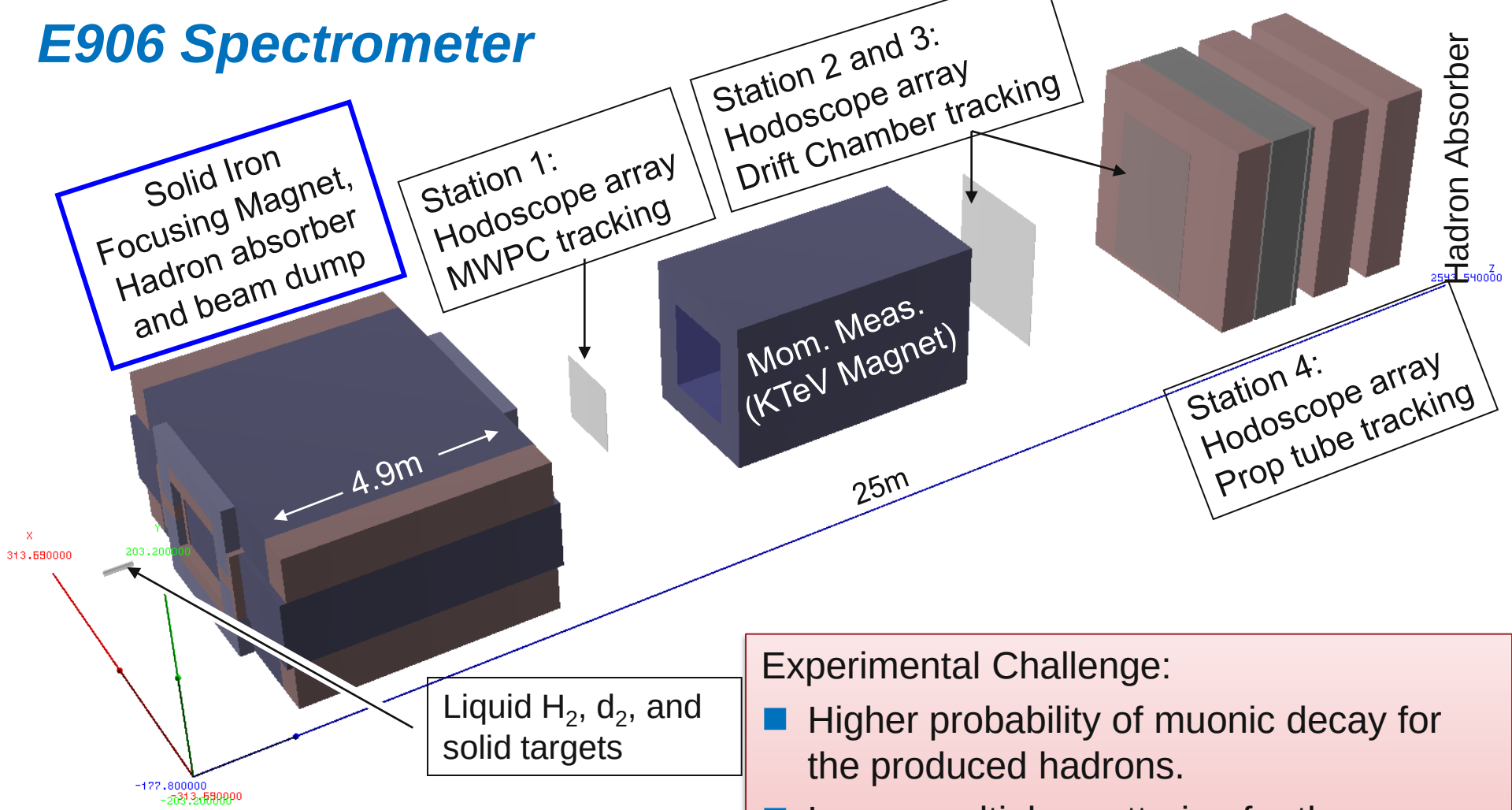
E906 Spectrometer



Solid iron magnet

- Reuse SM3 magnet coils
- Sufficient Field with reasonable coils
- Beam dumped within magnet

Experimental Challenge:

- Higher probability of muonic decay for the produced hadrons.
- Larger multiple scattering for the muon traveling through hadron absorber and solid magnet.
- Worse duty factor for beam structure.
- Higher singles rates.

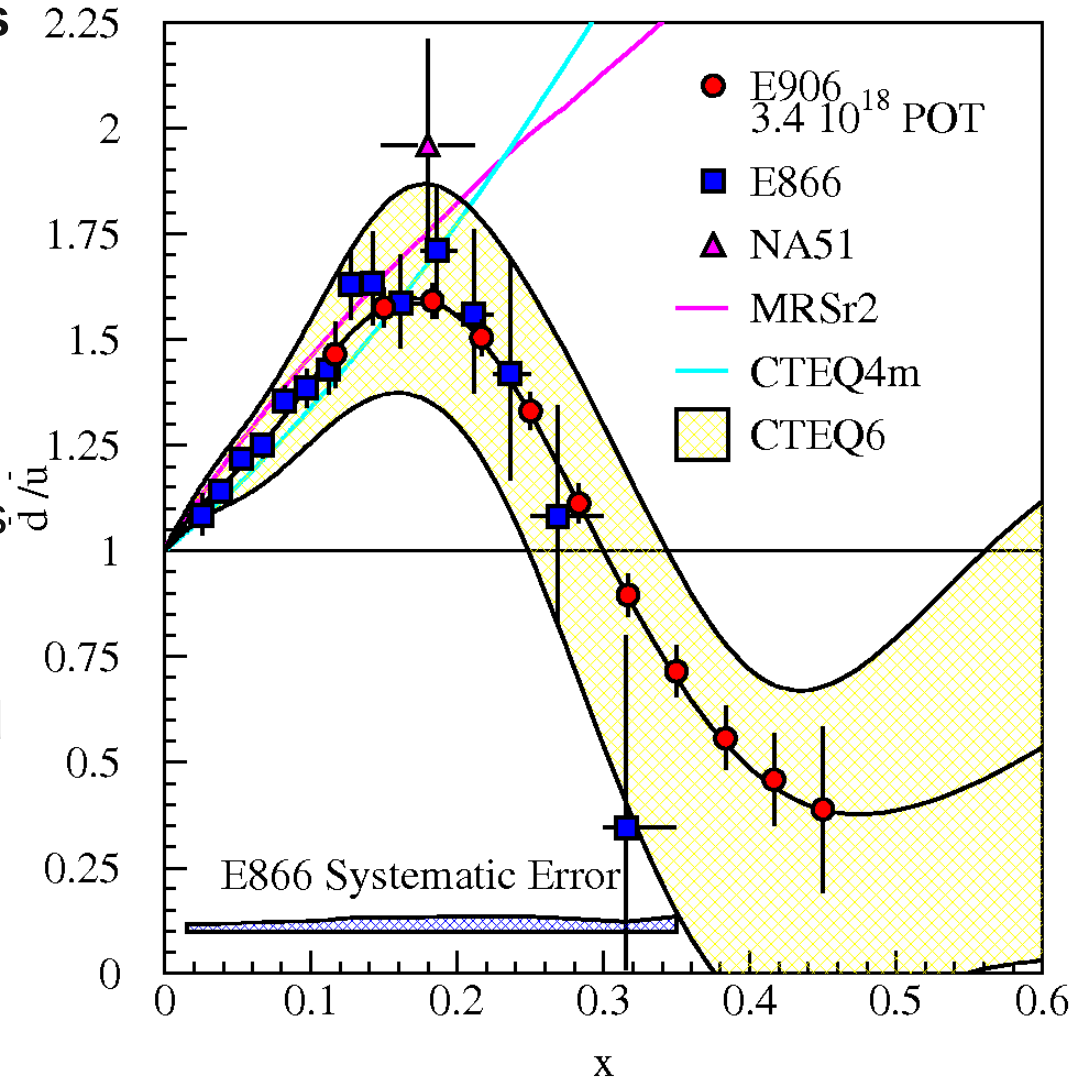
Extracting d-bar/-ubar From Drell-Yan Scattering

Ratio of Drell-Yan cross sections

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

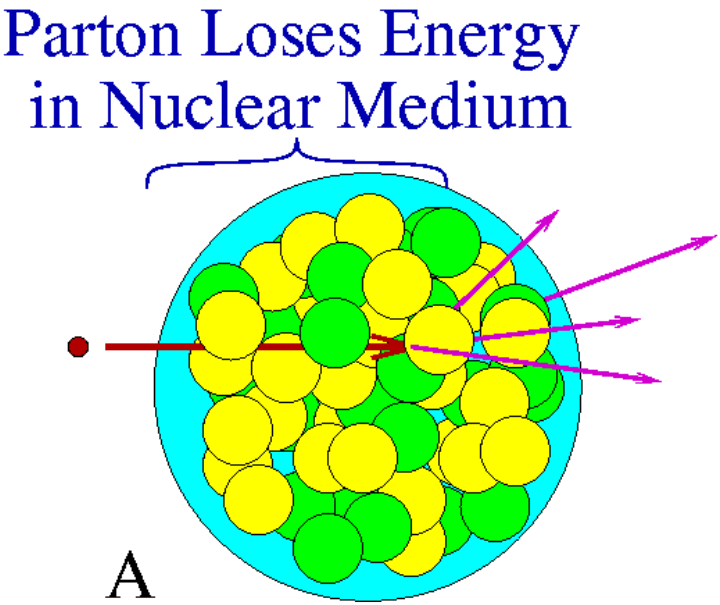
(in leading order—E866 data analysis confirmed in NLO)

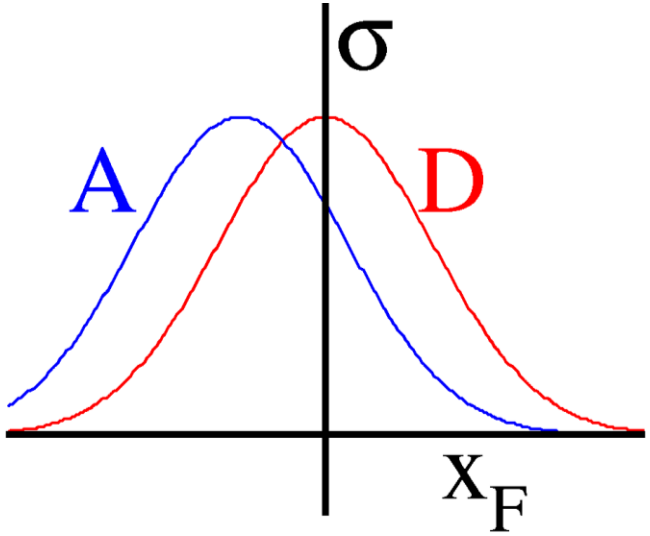
- Global NLO PDF fits which include E866 cross section ratios agree with E866 results
- Fermilab E906/Drell-Yan will extend these measurements and reduce statistical uncertainty.
- E906 expects systematic uncertainty to remain at approx. 1% in cross section ratio.



Partonic Energy Loss

- An understanding of partonic energy loss in both cold and hot nuclear matter is paramount to elucidating RHIC data.
- Pre-interaction parton moves through cold nuclear matter and looses energy.
- Apparent (reconstructed) kinematic values (x_1 or x_F) is shifted
- Fit shift in x_1 relative to deuterium

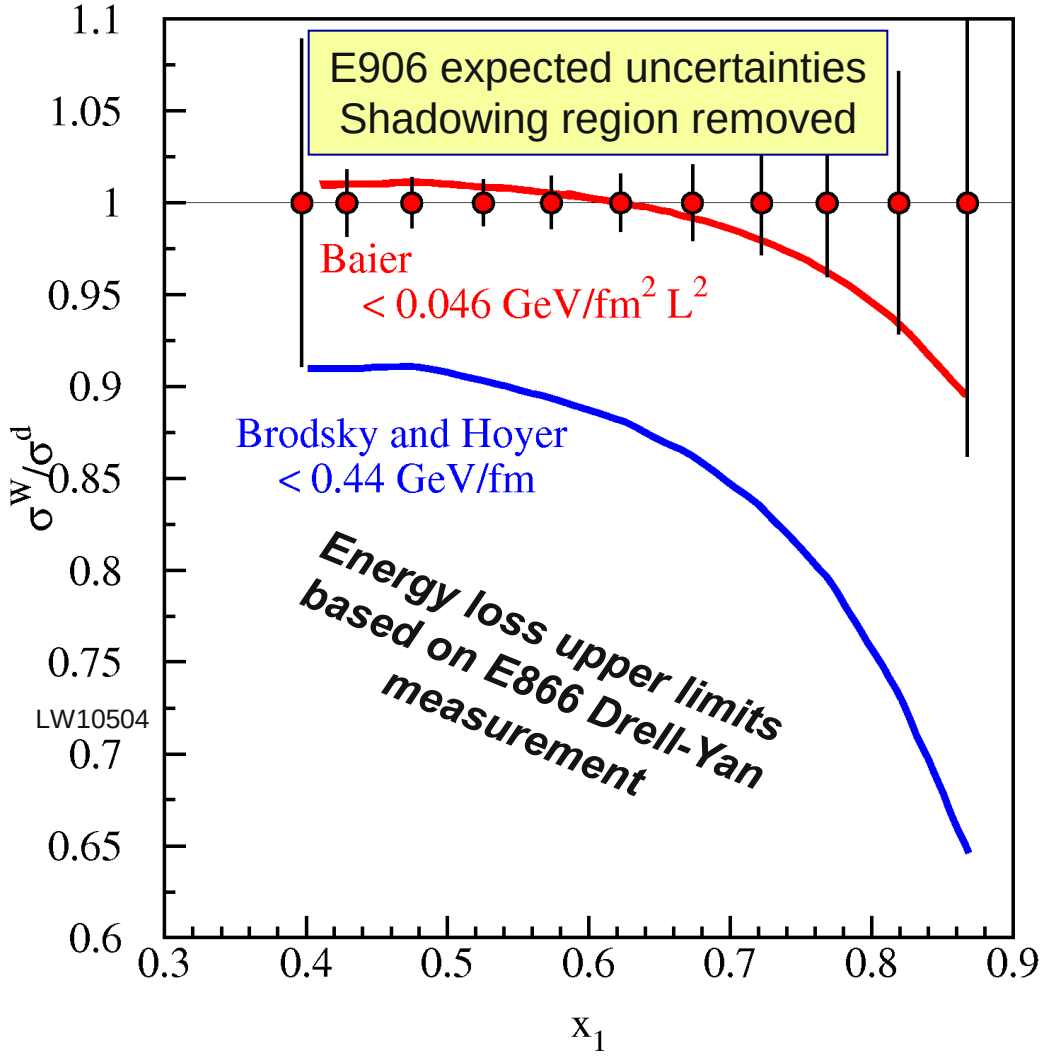




- Models:
  - Galvin and Milana $\Delta x_1 = -\kappa_1 x_1 A^{\frac{1}{3}}$
  - Brodsky and Hoyer $\Delta x_1 = -\frac{\kappa_2}{s} A^{\frac{1}{3}}$
  - Baier *et al.* $\Delta x_1 = -\frac{\kappa_3}{s} A^{\frac{2}{3}}$

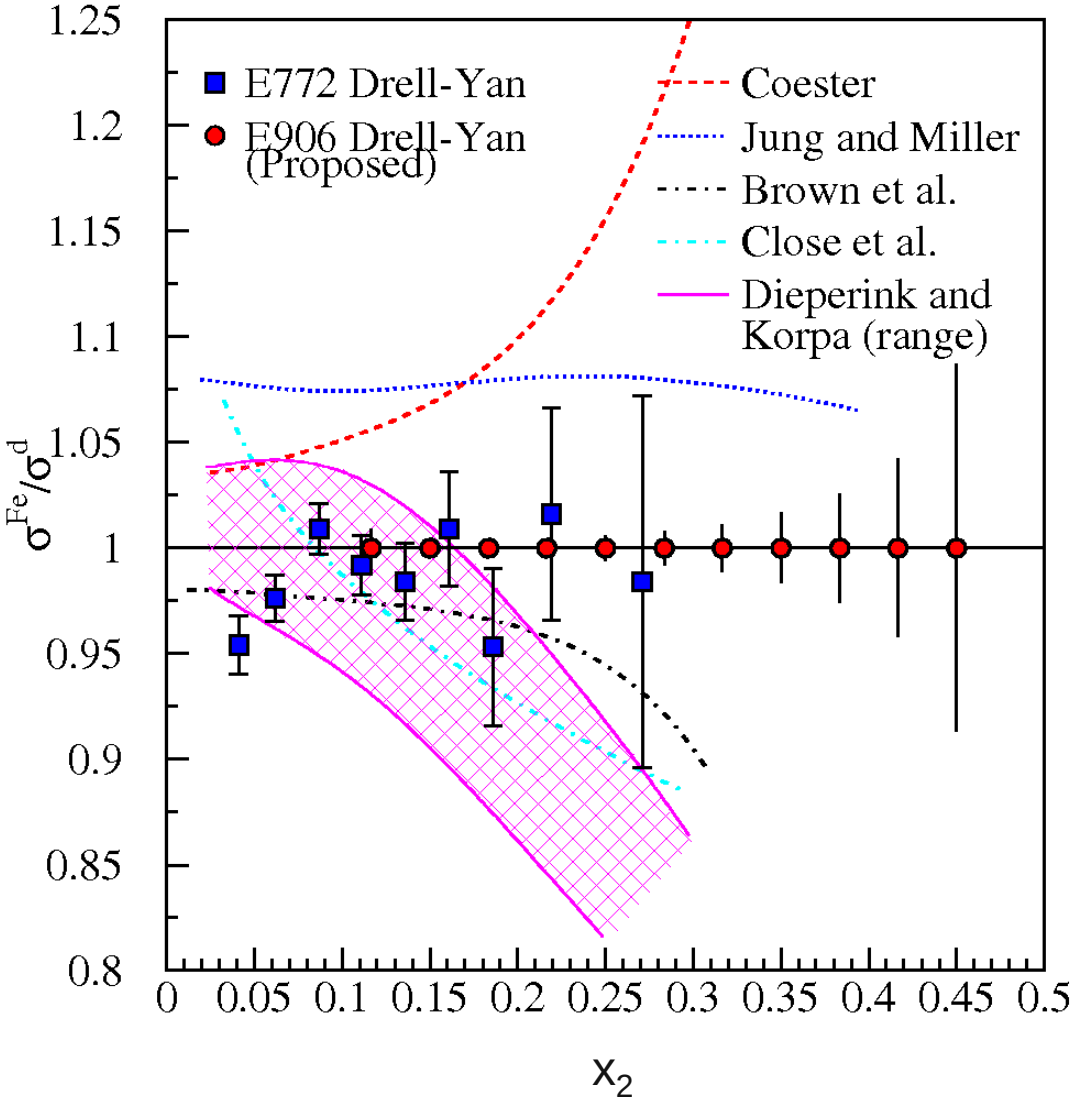
Parton Energy Loss

- Energy loss / 1/s
  - larger at 120 GeV
- Ability to distinguish between models
- Measurements rather than upper limits
- E906 will have sufficient statistical precision to allow events within the shadowing region, $x_2 < 0.1$, to be removed from the data sample

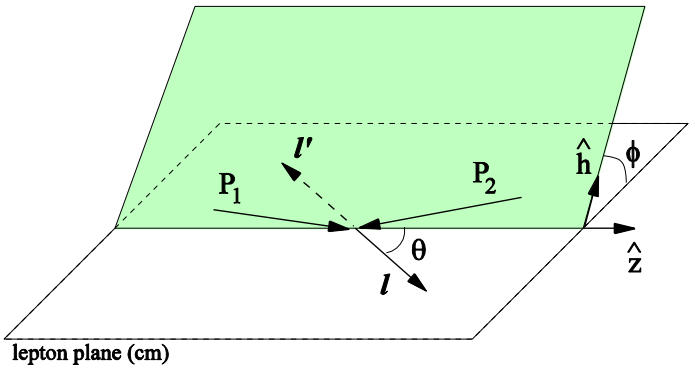


EMC effect of antiquark distribution?

- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual “Nuclear” mesons.
- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.
- Contemporary models predict large effects to antiquark distributions as x increases.
- Models must explain both DIS-EMC effect and Drell-Yan



Drell-Yan Decay Angular Distributions



Θ and Φ are the decay polar and azimuthal angles of the μ^+ in the dilepton rest-frame

Collins-Soper frame

A general expression for Drell-Yan decay angular distributions:

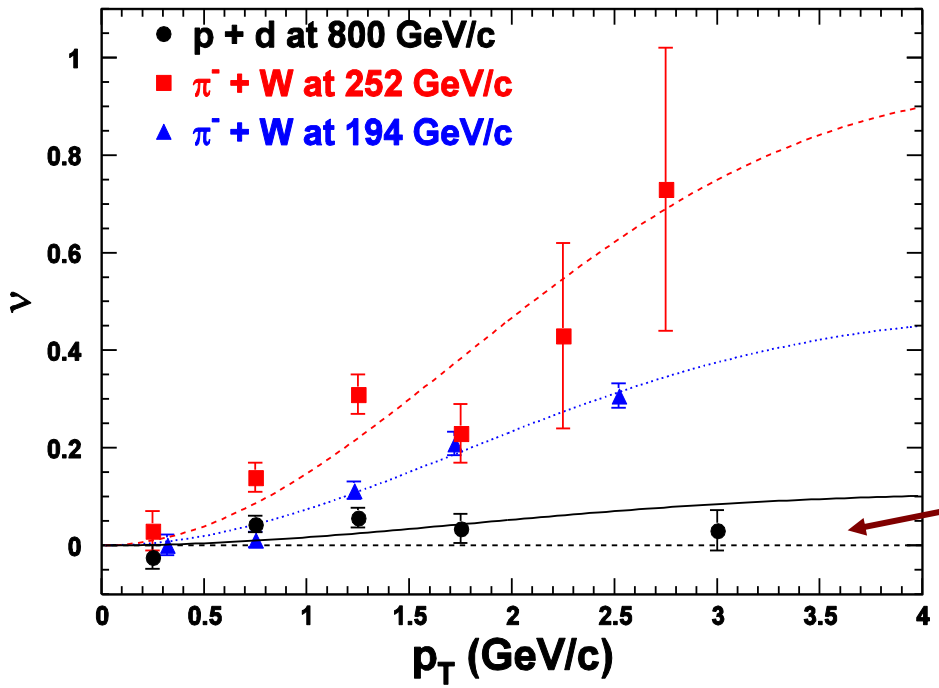
$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

Lam-Tung relation: $1-\lambda=2\nu$ **Phys. Rev. D 18, 2447–2461**

- Reflect the spin-1/2 nature of quarks (analog of the Callan-Gross relation in DIS)
- Insensitive to QCD - corrections

Azimuthal cos2Φ Distribution in p+p and p+d Drell-Yan

E866 Collab., Lingyan Zhu et al.,
PRL 99 (2007) 082301; PRL 102 (2009) 182001



Small ν is observed for p+d and p+p D–Y

With **Boer-Mulders function** $h_1^{\perp}$:

$\nu(\pi^- W \rightarrow \mu^+\mu^- X) \sim$ [valence $h_1^{\perp}(\pi)$] * [valence $h_1^{\perp}(p)$]

$\nu(pd \rightarrow \mu^+\mu^- X) \sim$ [valence $h_1^{\perp}(p)$] * [sea $h_1^{\perp}(p)$]

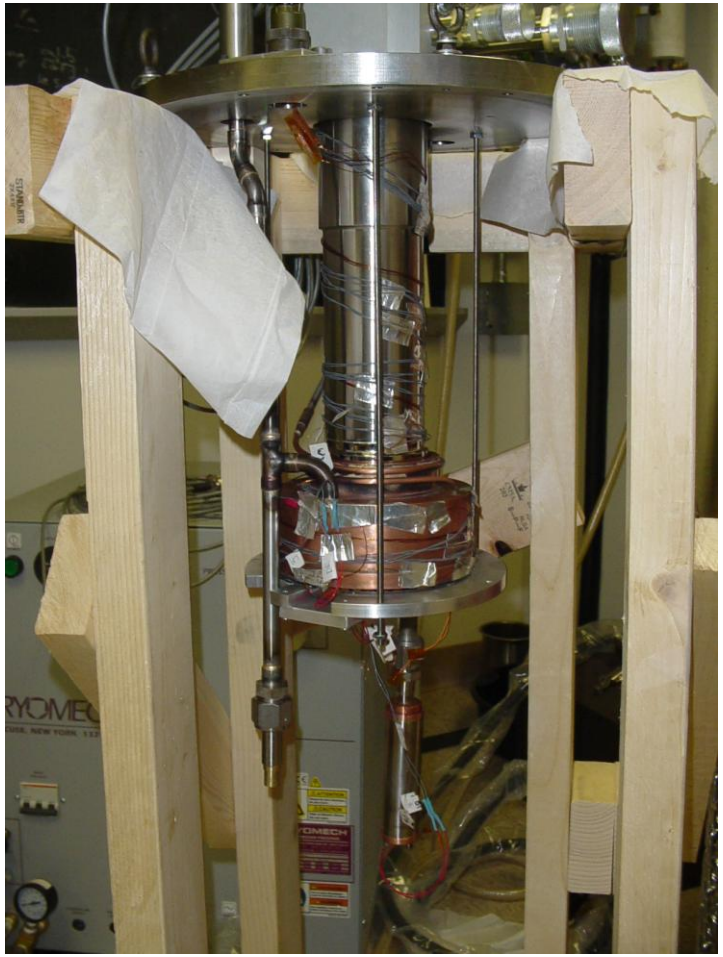
Sea-quark BM functions are much smaller than valence quarks

Timeline of E906

- 2002: E906 Approved by Fermilab PAC
- 2006: E906 funded by DOE Nuclear Physics
- **2008, Dec: Stage-II approval by Fermilab Director and MOU between Fermilab and E906 Collaboration finalized.**
- Construction and installation of spectrometer and readout electronics to be done in 2009 and upper half of 2010.

NM4/KTeV Hall

Liquid H/D Target

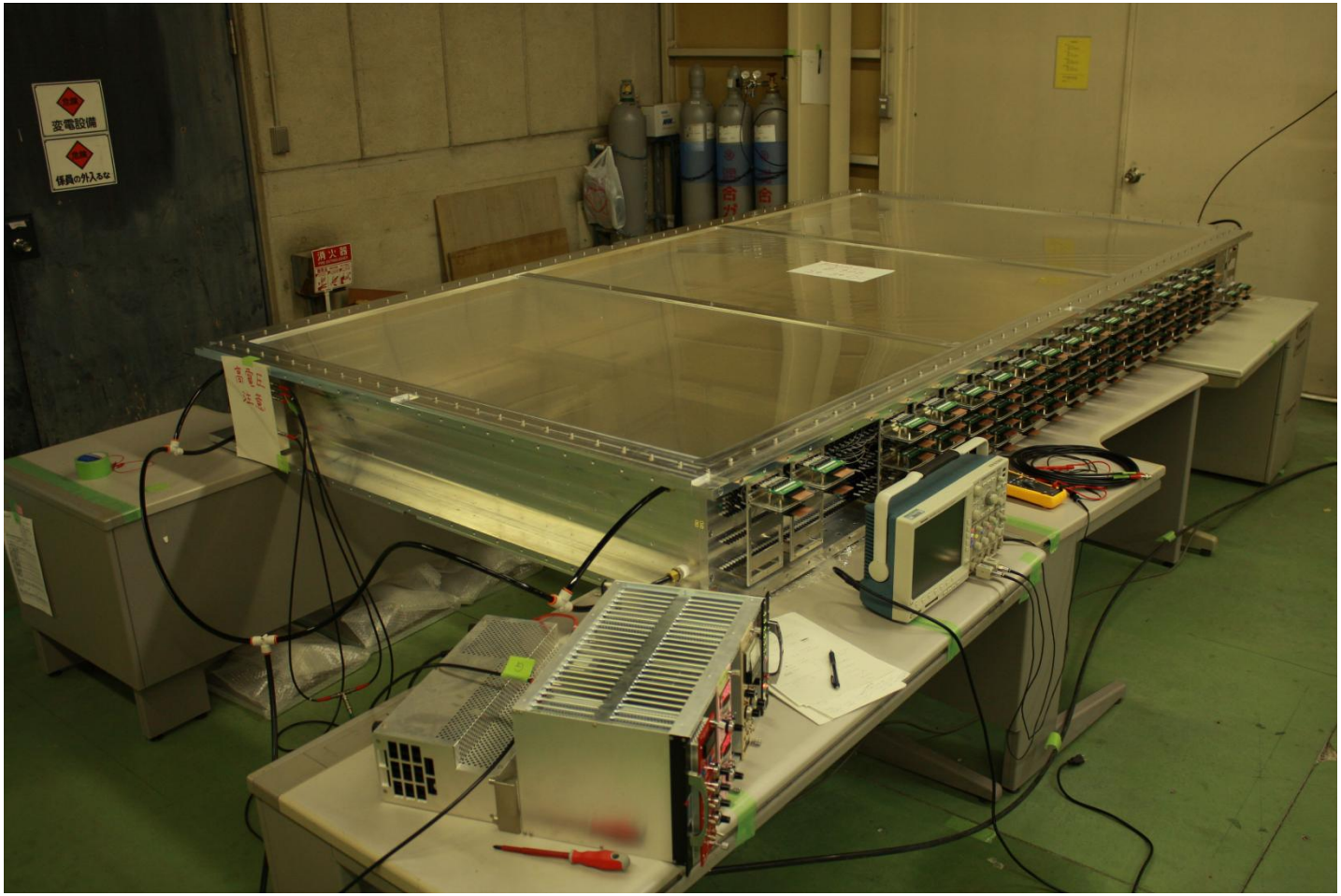


Focusing Magnet

KTeV Magnet

Station 2 and 3- (Drift Chambers)

Station 3+ (Drift Chamber)

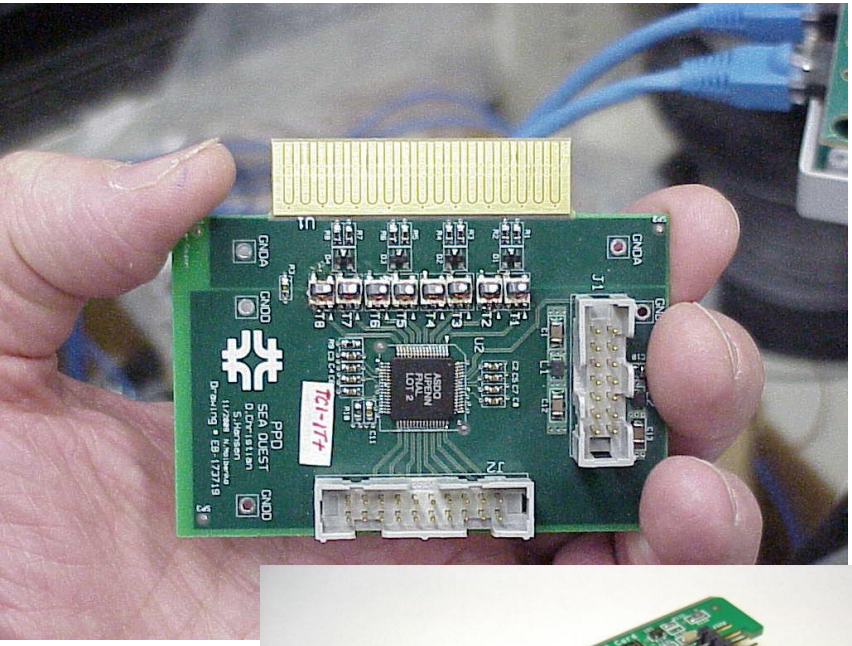


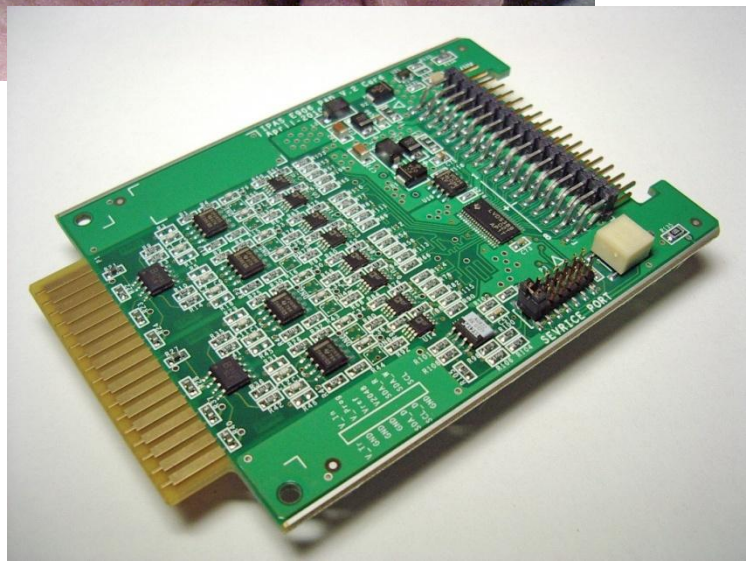
Station 4 (Proportional Tubes)

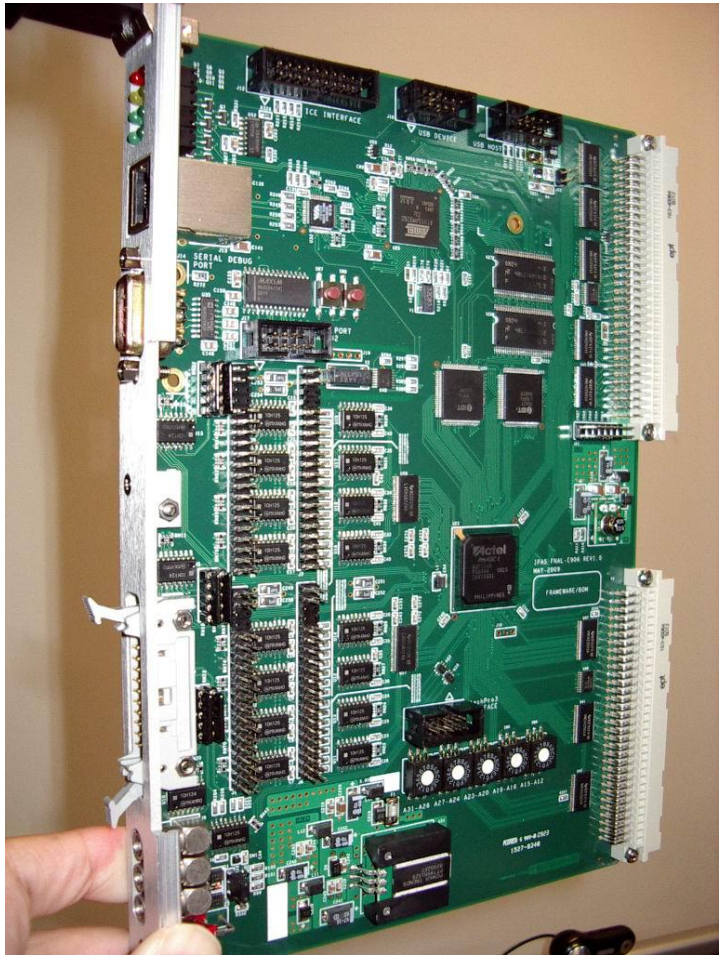
Qualitative HV scan and Signal Rates with Cosmic Rays (Ar/CO2)

Hodoscope (For online Dimuon Trigger)

Readout Electronics







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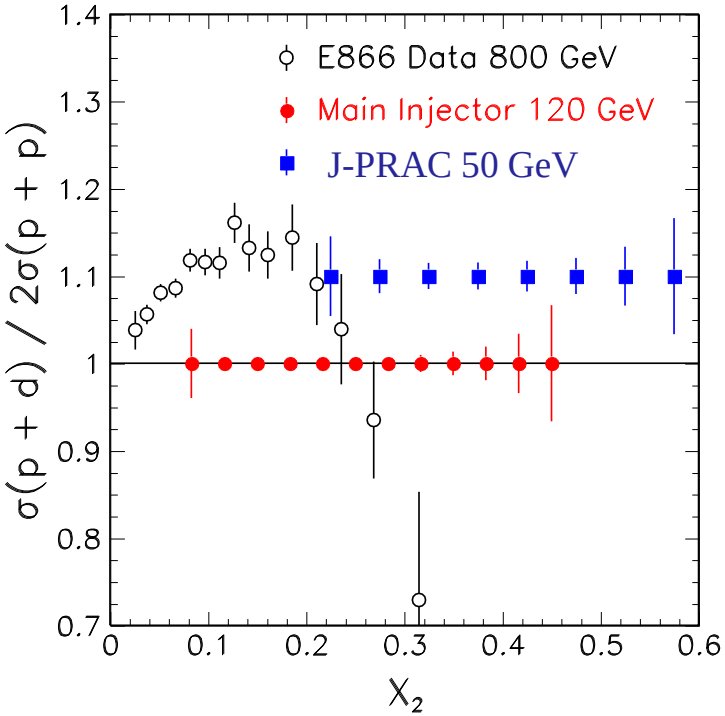
- Spectrometer construction and installation in 2009 and upper half of 2010.
- Commission run will start in July, 2010 and physics run is expected in the fall of 2010!
- Scheduled to run in 2010, 2011 and 2013 for 2 years of data collection

Possible Future Programs

- Possible future programs: polarized target and pionic Drell-Yan.
- Apparatus available for future programs at, *e.g.* RHIC, J-PARC.



Experiment Schedule

http://www.fnal.gov/directorate/program_planning/schedule/index.html

2010-2011 Fermilab Accelerator Experiments Schedule

This schedule will be updated regularly, as plans change.

Calendar Year		2010	2011
Tevatron Collider		CDF	CDF / OPEN
		DZero	DZero / OPEN
Neutrino Program	B	MiniBooNE	MiniBooNE #
	MI	MINERvA	MINERvA
		ArgoNeuT	
		MINOS	MINOS
SY 120	MT	Test Beam	Test Beam
	MC	OPEN	OPEN
	NM4	E-906/SeaQuest	E-906/SeaQuest

Draft 2010-13 Fermilab Accelerator Experiments' Run Schedule

Typically Revised Annually - This Version from October, 2009

Calendar Year		2010	2011	2012	2013
Tevatron Collider		CDF & DZero	CDF & DZero	OPEN	OPEN
Neutrino Program	B	MiniBooNE	MiniBooNE		OPEN
		OPEN	OPEN		MicroBooNE
	MI	MINOS	MINOS		OPEN
		MINERvA	MINERvA		MINERvA
		ArgoNeuT			
			NOvA		NOvA
SY 120	MT	Test Beam	Test Beam		Test Beam
	MC	OPEN	OPEN		OPEN
	NM4	E-906/Drell-Yan	E-906/Drell-Yan		E-906/Drell-Yan